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ON THE USE OF VERTICAL CROSS SECTIONS IN STUDYING ISENTROPIC FLOW

By CHARLES H. PIERCE

[Weather Bureau, Washington, D. C., October 1938]

The isentropic chart is proving more and more valuable to the synoptic meteorologist, but it has one disadvantage—it shows only a very thin sheet of the free atmosphere. Often the meteorologist wants a more complete picture of the upper air than given by the one or two isentropic charts that he may have at hand. This is especially true in the vicinity of frontal activity. To thus aid the meteorologist, and to serve as a helpful link between the isentropic chart and the surface map, vertical cross sections showing the arrangement of the various isentropic surfaces from the ground up to 5 or more kilometers are useful.

It has been found that the quantities to be represented in order to give the best thermodynamic interpretation of the cross section are potential temperature and the isentropic condensation temperature. These are expressed in degrees A. As supplementary data to these values, temperature, specific humidity, relative humidity, equivalent potential temperature, winds, and hydrometeors may be entered to aid in the final analysis of the cross section. In the examples presented here, solid lines are drawn through equal potential temperatures, and dotted lines represent equal isentropic condensation temperatures. Isotherms of potential temperature of course represent isentropic surfaces. Isentropic condensation temperature of a mass of air is defined as the temperature it would have if it were raised adiabatically without gain or loss of water vapor to the condensation level. On any one isentropic surface this value is a direct function of specific humidity and therefore can be used to indicate the moisture distribution in the air.

Proof of this is found in a paper by Byers.¹ Therefore lines of constant condensation temperature on an isentropic surface correspond to lines of constant specific humidity. However, in a cross section, several different potential temperatures occur so that θ is a variable and T_0 -isotherms do not correspond to q -isograms. For a given condensation temperature the specific humidity would be different at every level or pressure.

This variation of q with p for a given condensation temperature can be shown by differentiating equation (2) of Byer's paper holding T_0 constant, which according to equation (5) means e_0 constant.² We find that this variation for a difference of 100 mb at levels up to 5 km is 20 percent or less. In other words, for a T_0 of 14° C. at 1,000 mb we have a specific humidity of 10.3 grams per kilogram while at 900 mb it increases to 11.4 grams, which gives a variation of 10 percent. Isentropic condensation temperature is invariant in an adiabatic process as is specific humidity. Also, there is no appreciable change in the flow pattern when isotherms of isentropic condensation temperature are used in place of isograms of specific humidity

so that it seems reasonable to use it in place of specific humidity, especially after considering the advantages.

ADVANTAGES

One advantage is that a better thermodynamic interpretation can be derived from the use of the two values, potential temperature and condensation temperature. Since air cools approximately 1° C. per 100 meters of ascent in an adiabatic process, the height of the condensation level above 1,000 mb can be determined by subtracting the isentropic condensation temperature from the potential temperature at any point on the cross section and multiplying the difference by 100. Therefore, if there is a difference of 45° between potential temperature and condensation temperature for a certain particle of air on the cross section, condensation would be expected at 4,500 meters above the 1,000 mb level. If the particle in question is already located, let us say, at 4,200 meters, then it is close to condensation, but if it is at 1,200 meters then it must undergo considerable lifting along the isentropic surface before condensation takes place. The height of saturation above sea level can easily be found by adding the height above sea level of the 1,000-mb surface to the original height, which in the above case was 4,500 meters. Allowing, as a rough average, 100 meters for every 12 mb between the sea-level pressure and 1,000 mb, the height at which the pressure of 1,000 mb is located can roughly be estimated from the surface map. A slight error is introduced by assuming that the same pressure gradient exists at intermediate and high levels that is found at the earth's surface. However, this assumption is negligible during both winter and summer, amounting to not more than 200 or 300 meters.

An example of how the isentropic condensation temperature can thus be used is found in the cross section of January 11, 1938, from Omaha to Chicago (fig. 1). At 900 meters at Omaha a potential temperature of 287° and a condensation temperature of 265° are found. Subtracting one from the other we have a difference of 22° which means condensation might be expected at 2,200 meters above the 1,000 mb level. Because the air flow was directed toward Chicago, the sea-level pressure for that station, which was 1,011 mb, is taken. This places the 1,000 mb level at 100 meters above sea level. Adding this to 2,200 meters, we find that the condensation level for this element of air in the vicinity of Chicago is 2,300 meters above sea level. It is noted that the 285° isentropic surface slopes sharply to 2,600 meters at Chicago, therefore it would be expected that condensation would take place slightly west of Chicago if the particles having the same properties as those at Omaha were flowing up the slope. This is borne out by the fact that we find clouds on the 287° surface at Chicago.

¹ Byers, H. R. On the Thermodynamic Interpretation of Isentropic Charts, *Mo. WEA. REV.*, Vol. 66, pp. 63-68, March 1938.
² *Ibid.* fn. 1.

In the illustrations the symbolism used is the following: The thin solid lines represent isotherms of potential temperature drawn for every 5° C. The thin broken lines represent isotherms of isentropic condensation tempera-

ture with increasing stability. The symbols used in the illustrations are: cPw—continental Polar warm; mPk—maritime Polar cold; mPw—maritime Polar warm; mTk—maritime Tropical cold; mTw—maritime Tropical warm; S—Superior.

Of course the use of isotherms of isentropic condensation temperatures means that the condensation level must be found indirectly from the cross section. There are those, such as airway forecasters, who are not as interested in the flow pattern as they are in being able

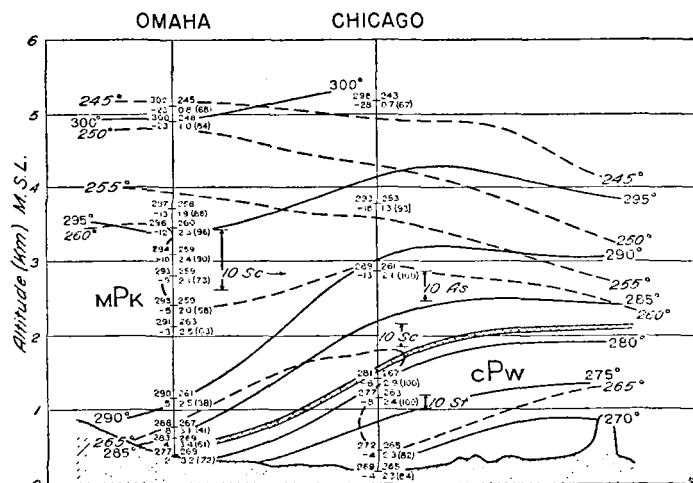


FIGURE 1.—Cross section, Omaha-Chicago, January 11, 1938.

ture drawn for every 5° C. The cross hatched lines represent warm fronts. The heavy solid lines represent cold fronts. The cross-hatched broken lines represent inactive fronts or surfaces of subsidence.

The four elements of the station data are arranged with the potential temperature at the upper left; isentropic condensation temperature at the upper right; temperature at the lower left; and specific humidity (Relative humidity) at the lower right.

The air mass symbols used are those of the thermodynamic air mass classification introduced by Bergeron. The significance of this classification is given in Willett's "American Air Mass Properties," Vol. II, No. 2, Paper in Physical Oceanography and Meteorology.

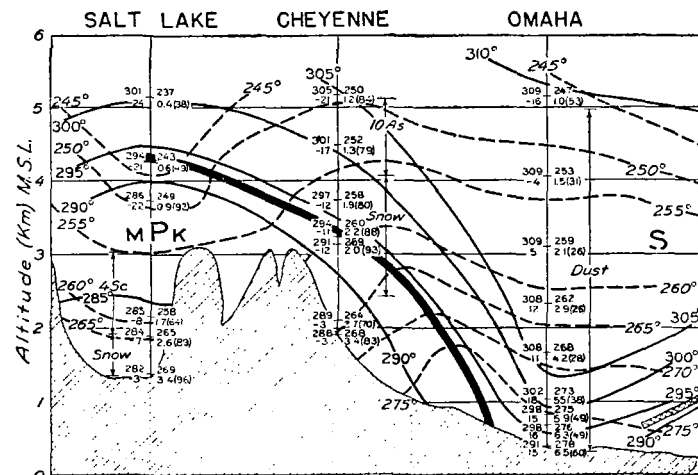


FIGURE 2.—Cross section, Salt Lake City-Omaha, March 18, 1938.

In addition to showing the source region, Bergeron's classification also gives an indication of the existing lapse rate of the air mass. The letter K (Kalt or Cold) indicates the air mass as a whole is colder than the surface over which it is traveling. In other words the lapse rate is conditionally unstable and the instability of the air column is increasing or remaining the same. The letter W (Warm) shows that the air mass is warmer than the surface over which it is traveling and is therefore stable

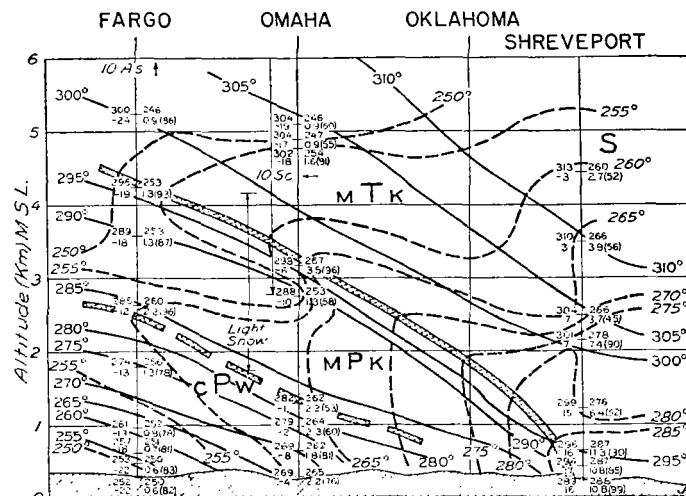


FIGURE 3.—Cross section, Fargo-Shreveport, February 15, 1938.

to tell directly upon examining the cross section what the condensation level is of any air parcel. If such is the case, then iso-lines showing the height of the condensation level may be drawn to replace isotherms of condensation temperature.

The easiest and quickest method of finding the condensation level is by subtracting the dew-point from the actual temperature for each significant level; this difference is multiplied by 100 because air cools approximately 1° C. per 100 meters. The product is added to the original height to give the height in meters above sea-level of the condensation level for direct vertical convection. The error is not appreciable if this condensation level is also used for advective motion along the isentropic surface. Iso-lines are then drawn through points having

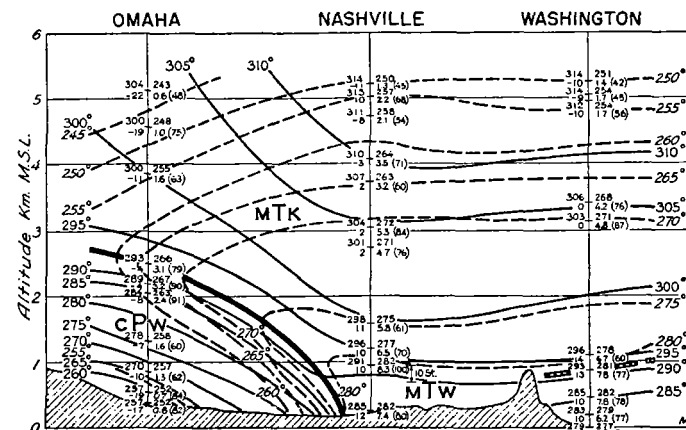


FIGURE 4.—Cross section, Omaha-Washington, February 18, 1938.

equal condensation levels and may be drawn for every 1,000 meters. By comparing these iso-lines with the actual height on the cross section, the nearness to saturation of the air can be seen at a glance.

An advantage of the T_0 -isotherms over isograms of specific humidity is that they give a more representative difference in moisture content in cold air and also there is no crowding of lines in the high moisture content of the tropical maritime air.

It will be noted then that the isentropic cross sections are constructed entirely of isotherms.

VALUE OF CROSS SECTIONS

The isentropic chart usually shows the approximate flow pattern for other surfaces not too far above and below it. During the winter, however, measurable precipitation can be produced from condensation taking place relatively low in the atmosphere and the isentropic charts may be too high to show what is really going on. Several times during the winter 1937-38 such was the case. The isentropic charts showed that condensation could not take place over a certain area, but precipitation of moderate amounts resulted within 24 hours. It was decided that the condensation occurred beneath the isentropic surface that was represented by the chart. This may have been due to a steeper slope of the lower isentropic surfaces or to a relatively higher moisture content in the lower air. A cross section in this area would have shown that while condensation would not occur at high levels, there might have been appreciable lifting in the lower air to produce saturation.

While there is not a really good example of this, the cross section that was just examined, that of January 11, 1938 (fig. 1) illustrates what is meant. The 295° surface is generally about as low as isentropic charts are constructed. It will be noticed that this surface has a very easy slope and that if the air at Omaha were dry we would not expect any condensation on this surface at Chicago. However, the 287° surface slopes up sharply from 900 meters at Omaha to 2,600 meters at Chicago. Even though the air is relatively dry (40 percent) at Omaha, we have already seen that it will become saturated before it reaches Chicago. The isentropic cross section shows then, not only the slope of one isentropic surface, but the slope of many.

Cross sections also show the layers of moist and dry air. Even if the slopes of the surfaces are found to be about the same throughout the atmosphere, it might be that the air at higher levels would be relatively dry while that in lower levels, below the surface of the isentropic chart, might be relatively moist so that little lifting would result in saturation. Namias in his recent article³ has ably pointed out the importance of knowing the position of the moist and dry layers for summer forecasting.

STABILITY

The cross section also aids in determining the stability of the atmosphere. When two isentropic charts are constructed, the stability of the layers between them can be determined by finding the difference between the pressures of the upper and lower surfaces. But again this depicts the stability of a very small part of the atmosphere which may not be representative of the whole. An example of this is found on the cross section of March 18 constructed from Salt Lake to Omaha (fig. 2). A stability chart that day was drawn between the 299° and the 303° surfaces. At Omaha a very stable layer was shown between these surfaces near 1 km. However, the air column above 1,500 meters has a lapse rate very close to the dry adiabatic

as is shown by the distance between the isotherms of potential temperature. On this particular day the inversion was so pronounced and the air so dry that this steep lapse rate was relatively unimportant, except that it maintained dust to high levels. As far as meteorological phenomena are concerned, a better example is Salt Lake City. If a stability chart had been drawn between the surfaces of 295° and 299° , the layer of air would have been very stable. But on the isentropic cross section it is noted that the air below 3,800 meters, and below the 286° isentropic surface, is conditionally unstable; in fact snow flurries are occurring at the time of the observation.

Conditional stability is shown on the cross sections by the distance between the θ -isotherms. As a rough estimate, conditional equilibrium at the temperatures ranging from 20° to 0° is represented by a distance of about 1,100 meters between the isentropic surfaces of every 5° . If the surfaces are closer together than this, the air is stable; if farther apart, it would be unstable with respect to moist air. If the air were unstable with respect to dry air, the potential temperature would decrease. This seldom happens except close to the ground during the heat of the day. Of course, the cross section can never take the place of the adiabatic chart in determining the stability of a column of air, but the cross section does show the relationship and changes of stability from one station to another.

CONVECTIVE INSTABILITY

The Rossby Diagram is the best chart for determining the convective stability, but it also can be roughly estimated from the cross section by studying the moisture distribution through the vertical. If it is found that through a thin layer the moisture decreases rapidly, then convective instability might be expected. Examining the layer further it might be found that the condensation level at the top was much higher than at the bottom, which would prove that it was convectively unstable. Such was the case in the layer between 2,200 and 2,500 meters at Shreveport February 15, 1938 (fig. 3). At the bottom of this isothermal layer is found a potential temperature of 301° with a condensation temperature of 278° . At the top θ is 304° and T_0 is 266° . This means that particles at the bottom of the layer will have a condensation level at 2,300 meters and those at the top will reach condensation at 3,800 meters. With these air particles streaming up the warm front, it would be expected that this stable layer would tend to become unstable. This is shown by the spreading of the isotherms toward Omaha. Also the solid cloud deck suggests convective equilibrium. Somewhere between San Antonio and Omaha there must have been violent overturning. This is also suggested by the heavy rain and thunderstorms that occurred in northern Texas and southern Oklahoma, Wichita Falls reporting 4.18 inches of rainfall within a period of 12 hours, with a thunderstorm.

RELATIONS TO FRONTS

Rossby has suggested⁴ that "air mass boundaries must coincide with isentropic surfaces." During the past winter an effort was made by the Air Mass Section of the Weather Bureau to place fronts along the isentropic surfaces. It was generally found that the fronts followed these surfaces quite consistently. However, a leeway of two or three degrees on either side of the isentropic surface was allowed because of personal and instrumental

³ Thunderstorm forecasting with the aid of isentropic charts, *Bul. Am. Met. Soc.*, vol. 19, No. 1, 1938.

⁴ Isentropic analysis, *Bulletin of the American Meteorological Society*, vol. 18, No. 6-7, pp. 201.

error. Also on a long north-south cross section there must be some radiational effect.

Fronts are found where there is a packing of the isentropic surfaces above which there is a normal lapse rate. At the surface it would normally be expected that the front would start where the first isentropic surface in the cold air mass cuts the ground. This would probably be approximately true during the heat of the day, but because the aerological observations are taken in the early morn-

If fronts are drawn along isentropic surfaces, some difficulty is experienced in drawing occluded fronts and fronts aloft. So far we have not been able to get a cross section through a clear-cut occluded front, therefore, no study has been made of them. On the west coast where there is the greatest number of occlusions, the aerological stations are too widely separated to make a detailed study of them. It is the author's belief, and that of his colleagues in the Air Mass Section, that cold and warm type occlusions would have a history such as appears in figure 7. The original cold and warm front would be maintained for awhile as a wave aloft. When the occlusion was new the front might pass through the isentropic surfaces at their greatest curvature, but due to the rapid horizontal mixing in this stable layer the front would soon dissipate. When this occurred a new front would appear on the first isentropic surface that met the ground in the colder air mass.

Although no study has been made of fronts aloft, it is believed that one would be located at the top of an inversion below which the isentropic surfaces sloped sharply. A cold front aloft would appear on the cross section such as pictured in figure 7.

If fronts are placed on isentropic surfaces, then potential temperature becomes an important criterion in determining the boundary properties of air masses. It was noted during the winter 1937-38 that the tropical air warm front usually occurred on the isentropic surfaces between 290° and 293° (for Pacific tropical fronts, 295° to 300°). If the moist air which appears on the 293° surface is called maritime tropical air, then the dry cold air on the same surface that appears at higher altitudes, say about 5 kms, should not be called Polar air. The best name for this air probably is Superior, because it is the same type of air that is found in the warm dry tongues at low altitudes in the southern United States.

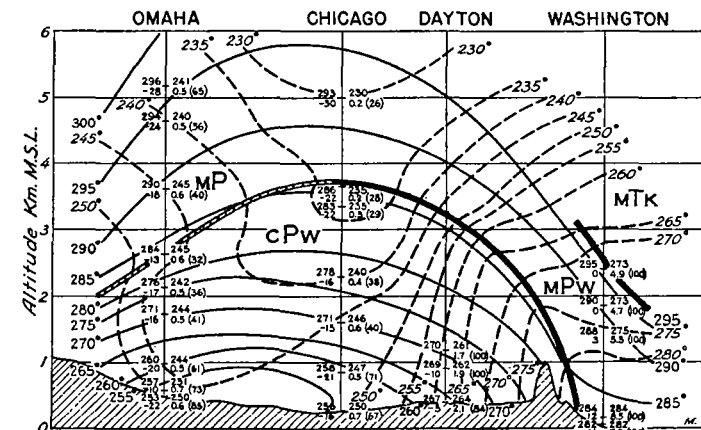


FIGURE 5.—Cross section, Omaha-Washington, January 31, 1938.

ing the effects of radiational cooling in the lower air are prominent, and we found that below 1 km the front passes through the isentropic surfaces at the point of their greatest curvature. This would also be true of tropical air in the winter time as it is cooled by its movement northward.

The above points are illustrated in figure 4, a cross section from Omaha to Washington of February 18, 1938. The front is located on the 293° surface. This is the top of the crowded isotherms and above this the isotherms are well spaced. At Nashville there is practically an isothermal layer in the first 1,000 meters due to cooling so that the potential temperature at the ground is 285° , and at 1,100 meters it is 293° . The front was west of Nashville at the time so that it must cut through several surfaces below 1 km. This cold front has an average slope between the surface front and Omaha of 1/300 in the plane of this cross section. Fronts as shown on cross sections along the isentropic surfaces are not as steep as those shown on cross sections where one takes the liberty of drawing fronts through the surfaces. However, there were a few cases during the winter that cold fronts had a very steep slope. One of these is shown in figure 5, an east-west cross section drawn for January 31, 1938. Here again the isentropic surfaces were packed just below the front, and because this is stable continental polar air, there is crowding all through the air mass.

Warm fronts are located on the cross section in much the same manner as cold fronts. Quite often, however, the temperature and wind discontinuity are so weak, on and near the earth's surface, that the front is impossible to find on the synoptic chart, yet it may be very distinct aloft. Such was the case on February 17, 1938, on the cross section from Shreveport to Detroit shown in figure 6. A distinct discontinuity is found on the 293° θ -isotherm at Nashville and Detroit but the location of the front was very doubtful on the synoptic chart because it was so nearly horizontal.

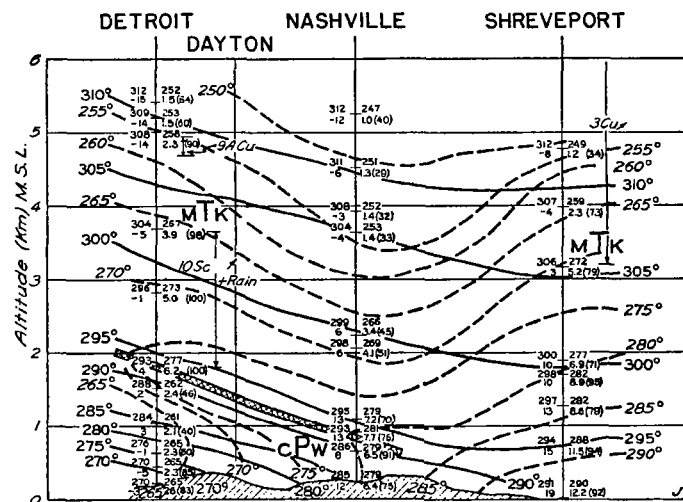


FIGURE 6.—Cross section, Detroit-Shreveport, February 17, 1938.

Placing fronts on isentropic surfaces also means that there may not be any front between Superior air and maritime Tropical air. However, if dry air overlies moist air, then, according to Namias,⁵ there would be an inversion and an inactive front between them. A cross section showing no fronts between maritime Tropical air and Superior air is that of February 17 (fig. 6). It is noted that the condensation temperature lines dip sharply from

⁵ Structure and Maintenance of Dry Type Moisture Discontinuities not Developed by Subsidence. *Mo. WEA. REV.*, vol. 64, No. 11, November 1936.

Shreveport to Nashville and then curve upward again to Detroit.

In conclusion, the cross section constructed with isotherms of potential temperature and isotherms of condensation temperature has the following advantages over one drawn which uses temperature and specific humidity: first, it has thermodynamic significance because the nearness to saturation of any point can be determined; second,

it roughly shows the convective instability of the air as was pointed out on figure 3; third, the slope of many isentropic surfaces is shown; and finally, because fronts follow isentropic surfaces, the position and slope of the fronts which cut the cross section plane can be identified.

The author wishes to express his gratitude to Dr. H. R. Byers for his able guidance and many helpful comments during the preparation of this paper.

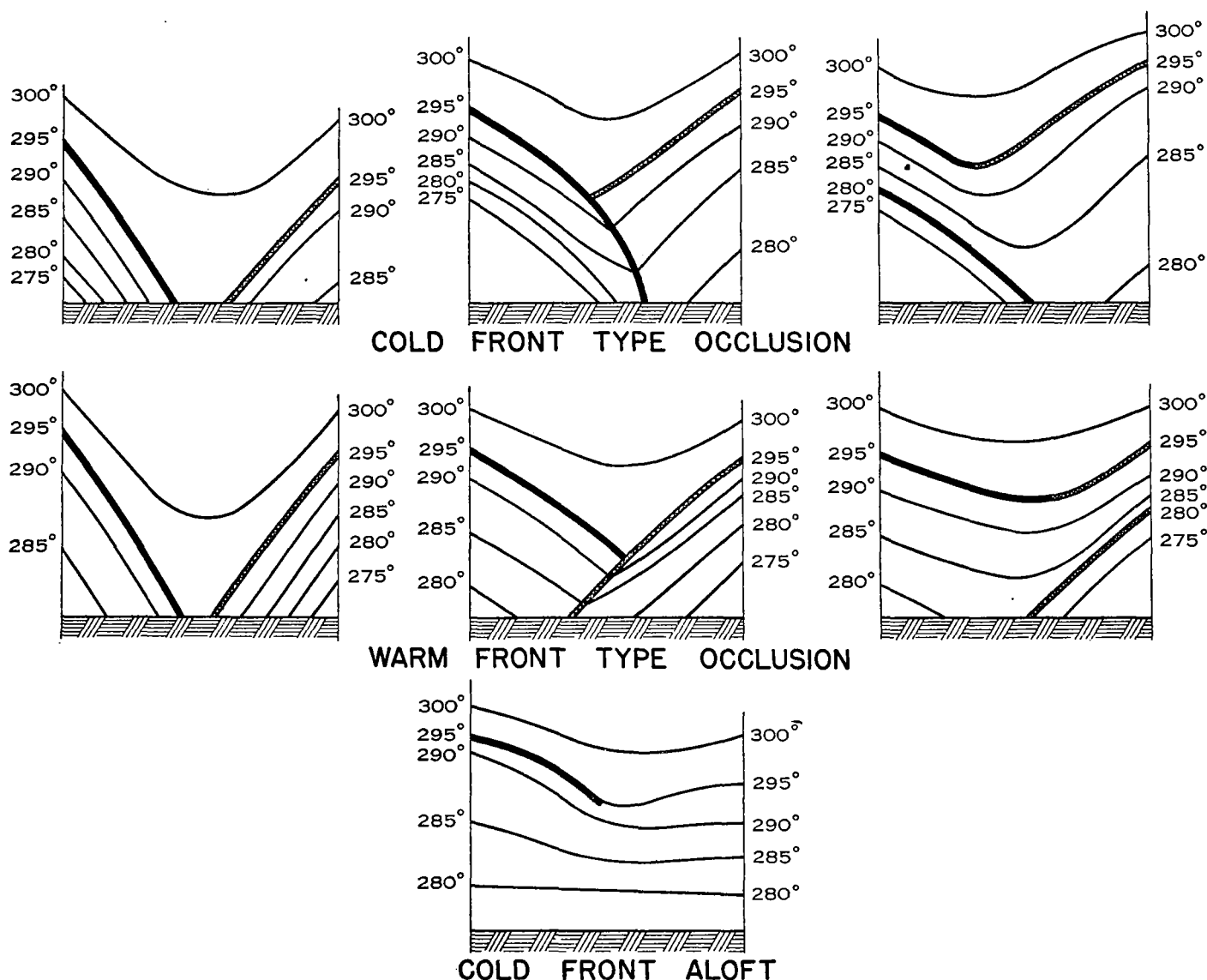


FIGURE 7.—Cross sections showing possible history of frontal positions on isentropic surfaces in cold- and warm-front-type occlusions and cold front aloft.

A PRACTICAL METHOD FOR COMPUTING WINDS ALOFT FROM PRESSURE AND TEMPERATURE FIELDS

By EDWARD M. VERNON and E. V. ASHBURN

[Weather Bureau, Oakland, Calif., May 1938]

The Weather Bureau's network of pilot-balloon observations supplies, as a rule, all the information on winds aloft required for the operation of aircraft. However, it is not an infrequent occurrence for current wind-aloft data to be missing over a large area, due to the presence of low cloud or other weather conditions which interfere with pilot-balloon observations. It is during such weather

conditions, which either prevent or greatly limit pilot-balloon observations, that the airplane pilot is most dependent upon information concerning the winds in the upper air. For this reason it has long been desirable to have a practical method for determining the winds aloft at various altitudes without having to rely entirely upon pilot-balloon data.